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INVESTIGATION OF THE BEHAVIOR OF THIN-WALLED PANELS WITH CUTOUTS

By A. A. Podorozhny

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INVESTIGATION OF THE BEHAVIOR OF
THIN-WALLED PANELS WITH CUTOUTS¹

By A. A. Podorozhny

The present paper deals with the computation and methods of reinforcement of stiffened panels with cutouts under bending loads such as are applied to the sides of a fuselage. A comparison is made between the computed and test results. Results also are presented of tests on panels with cutouts under tensile and compressive loads.

NOTATION

H	height of beam (fig. 5)
δ	thickness of skin
α	angle of inclination of waves of buckled beam to spars
σ_1	tensile stress
σ_2	compressive stress
k	ratio of stresses σ_2/σ_1
L	length of beam
l	spacing of transverse stiffeners (ribs)
h	spacing of longitudinal stiffeners (stringers)
F_{sp}	cross-sectional areas of top and bottom spars

¹Report No. 454 of the Central Aero-Hydrodynamical Institute, Moscow, 1939.

F_{st} cross-sectional area of stringers
 F_{ri} cross-sectional area of intermediate ribs
 F_{ro} cross-sectional area of outermost ribs
 $P = Q$ external force
 τ tangential stress in skin
 τ_{cr} critical tangential stress in skin at loss of equilibrium

STATEMENT OF PROBLEM

The presence of cutouts in the fuselage brings about a redistribution of the forces in its elements and a lowering in the over-all strength of the structure. A method is required therefore for strengthening the beam in such a manner that the effect of the cutouts may largely be eliminated. This problem as yet has been touched upon only slightly in the literature by investigators.

Belyakov (reference 1) in his paper considers cutouts of isolated sections and determines for these the centers of stiffness. As has been shown by experiment (fig. 1), the actual centers of stiffness of structures (fuselages) differ considerably from those computed. This is due to the fact that in determining the centers of stiffness of isolated cross sections no account is taken of (1) the effect of the neighboring closed sections on the open ones, (2) the effect of the cutout framing, and (3) the effect of the joint between fuselage and wing.

In the experimental work of M. I. Naiman (reference 2) the effect of cutouts and of the flanges around the cutout in a thin wall after loss of equilibrium is investigated. As may be seen from figure 2, the cutout flange lowers the stress concentration by about 16 percent. The flanging thus substitutes to a certain extent a stiffener frame around the cutout.

In the text book of Timoshenko and Lessels (reference 3) on applied structural theory, a computation formula is given for determining the maximum normal stresses in a thin-walled beam with cutouts for bending under a concentrated force. This formula shows that even a slotlike cutout produces an effect, the maximum normal stress being increased.

In a paper by M. I. Naiman (reference 4) an investigation is made of rectangular beams with cutouts under a bending moment and the following conclusions are reached: If the beam is loaded in bending by a force at one end and the cutout is located along the depth of the beam at a distance not less than 3 to 4 times its diameters, the maximum normal tensile and compressive stresses will be of the same magnitude as in the case of a beam without cutouts.

As follows from a test conducted on thin-walled duralumin beams with various cutouts (figs. 3 and 4), the Timoshenko-Lessells formula corresponds to real conditions. The conclusion of Naiman, however, is valid only for the case of pure bending. From the curves of figure 4, it is seen that the presence of cutouts located at a distance of four times its diameters from the edge produced, according to experiment, an increase in the maximum normal bending stress of 30 percent and according to the Timoshenko-Lessells formula, of 43 percent as compared to the maximum normal stress obtained by Naiman for the beam without cutouts. The circles in figure 3 indicate the location of the tensiometers while the straight lines through the circles indicate the gage lengths of the deformations. The positive numbers on the figure correspond to the normal tensile stresses and the negative numbers to the normal compressive stresses.

COMPUTATION OF THIN-WALLED BEAMS REINFORCED BY A SYSTEM OF LONGITUDINAL AND TRANSVERSE STIFFENERS

In this section a computation will be made of thin-walled beams without cutouts loaded by a concentrated force at the end. The ribs are assumed to be hinge-jointed to the spars. Actually there is a certain effect of the stiffness of the joints (frame rigidity) shown by experiment to be about 4 percent.

To determine the tensile and compressive stresses in the skin after loss of equilibrium, the following formulas (reference 5) will be used:

$$\sigma_1 = \frac{1}{1 + k} \frac{2\tau}{\sin 2\alpha} = \frac{2\tau - \tau_{cr}}{\sin 2\alpha} \quad (1)$$

$$\sigma_a = \frac{k}{1+k} \frac{2\tau}{\sin 2\alpha} = \frac{\tau_{cr}}{\sin 2\alpha} \quad (2)$$

where

σ_1 tensile strength

σ_a compressive stress

The character of the stresses σ_1 and σ_a is indicated on figure 5.

The coefficient k is determined by the formula

$$k = \frac{1}{\frac{2\tau}{\tau_{cr}} - 1} = \frac{\tau_{cr}}{2\tau - \tau_{cr}} \quad (3)$$

The tangential stresses τ are determined by the formula

$$\tau = \frac{QS_{ef}}{I_{ef}\delta} \quad (4)$$

where

Q shearing force

S_{ef} effective statical moment

δ thickness of skin

I_{ef} effective moment of inertia of the cross section

By the term "effective" is indicated that in computing S_{ef} and I_{ef} not the entire skin but only a part was taken in the computation. The cross-sectional area of such strips in the region under compression is taken equal to $30\delta^2$ (δ is the thickness of the skin) and in the region under tension 85 percent of the cross-sectional area of the skin.

The critical tangential stress τ_{cr} corresponding to the equilibrium breakdown of the skin may be determined by the formula

$$\tau_{cr} = 34,300 \left(110 + \frac{75}{\beta^2} \right) \left(\frac{\delta}{h} \right)^2 \quad (5)$$

where

$\beta = l/h$ and l is the long side.

Up to the instant when the skin of the beam has lost its equilibrium, the ribs receive no load from the tangential stresses; the spars and stringers are loaded by the normal stresses due to the bending moment. After the loss of equilibrium, however, the ribs are loaded by the skin with compressive forces and the spars and stringers are loaded by axial forces in addition to the normal stresses due to the bending moment. These forces, taken up by the ribs, spars, and stringers, result from a stress in the skin equal only to the difference between the tensile and compressive stresses, that is,

$$\sigma_{1d} = \sigma_1 - \sigma_2 = \frac{2(\tau - \tau_{cr})}{\sin 2\alpha} \quad (6)$$

where σ_{1d} represents the difference between the tensile and compressive stresses σ_1 and σ_2 shown in figure 5.

If the stiffness of the stringers to bending in the plane of the skin is small, the stresses in the skin of the neighboring panels will somewhat equalize. The resultant stresses in the spars, stringers, and ribs of a multipaneled beam are determined by the formulas:

Stress in the top spar:

$$\sigma_{sp't} = \frac{M}{I_{ef}} y_v - \frac{N}{F_{sp}} \quad (7)$$

Stress in the bottom spar:

$$\sigma_{sp'b} = - \frac{M}{I_{ef}} y_n - \frac{N}{F_{sp}} \quad (8)$$

Stresses in the stringers:

$$\sigma_{st} = \pm \frac{M}{I_{ef}} \bar{y} - \frac{N_1}{F_{st}} \quad (9)$$

The axial forces N and N_1 are determined by the formulas

$$N = \frac{\tau - \tau_{cr}}{2} h\delta \cot \alpha \quad (7')$$

$$N_1 = (\tau - \tau_{cr}) h\delta \cot \alpha \quad (9')$$

The stress in the intermediate ribs:

$$\sigma_{ri} = \frac{(\tau - \tau_{cr}) h\delta}{F_1} \tan \alpha \quad (10a)$$

The stress in the outermost ribs:

$$\sigma_{ro} = (\tau - \tau_{cr}) \left(\frac{h\delta}{2F_{II}} - \tan \alpha + \frac{y\delta}{F_{II}} \right) \quad (10)$$

where

F_{sp} cross-sectional area of the spar + $15\delta^2$

F_{st} cross-sectional area of stringer + $30\delta^2$

F_I cross-sectional area of an intermediate rib + $30\delta^2$

F_{II} cross-sectional area of an end rib + $15\delta^2$

M bending moment

I_{ef} effective moment of inertia of a cross section

y_v and y_n distance from neutral axis of beam to element under consideration (tensile and compressive zones)

\bar{y} distance from neutral axis of beam to stringer under consideration

y ordinate shown in figure 5

In the case of a beam constructed of various materials it is necessary in formulas (7), (8), (9), and (10) to take account of the differences in the moduli. A numerical example for such a beam is given below.

COMPUTATION OF THIN-WALLED BEAM WITH CUTOUT

In this section thin-walled beams with cutouts will be computed. Computation formulas will be derived with the aid of which it will be possible to determine the stresses and select stiffener members for framing the contour of the cutout.

The presence of a cutout decreases the shear cross-sectional area of the beam by the amount $F = \delta b$. (See fig. 6.) As a result, the tangential stresses in a section with cutout increase in magnitude. Use will be made of the notation

$$Q' = \tau b \delta \quad (11)$$

where

τ tangential stress in section without cutout

b depth of cutout

δ thickness of skin

The dimensions of the framing strip are determined by the conditions:

$$Q' = b \delta \tau = b' \delta' \tau'$$

whence

$$\delta' = \frac{b \tau \delta}{b' \tau'} \quad (12)$$

where

δ and δ' thicknesses of initial skin and stiffening strip, respectively

τ and τ' tangential stresses in initial skin before formation of a cutout and in stiffening strip, respectively

b and b' depth of cutout and width of stiffening strip, respectively

Formula (12) may be expressed in terms of the normal stresses in the following form:

$$\delta' = \frac{b\delta\sigma_1}{b'\sigma'} \quad (13)$$

where σ_1 and σ' are the respective tensile stresses in the initial skin and in the stiffening strip.

The distributed loads acting on the stiffeners bordering the cutouts (fig. 6) are determined by the following formulas:

$$q_r = (\tau - \tau_{cr}) \delta \cot \alpha \quad (14)$$

$$q_{st} = (\tau - \tau_{cr}) \delta \tan \alpha \quad (15)$$

$$t = \delta_{isp} \delta \sin \alpha \cos \alpha = (\tau - \tau_{cr}) \delta \quad (16)$$

In computing the horizontal stiffeners (parallel to the stringers), they may be assumed as beams with clamped ends in the case where they are extended to the following ribs. (See fig. 6.) In this case, the normal stresses for the center of the cutout span ($a/2$) of the stiffener frame section is determined by the formula

$$\sigma_{a1} = \pm \frac{q_{st} a^2}{24I_1} y = \pm \frac{(\tau - \tau_{cr}) a^2 \delta y}{24I_1} \tan \alpha \quad (17a)$$

Similarly, the stresses in the vertical stiffener sections (parallel to the ribs) for the center of the cutout ($b/2$) are determined

$$\sigma_{b_1} = \pm \frac{q_r b^2}{24 I_2} \quad x = \pm \frac{(\tau - \tau_{cr}) b^2 \delta x}{24 I_2} \cot \alpha \quad (18a)$$

In formulas (17) and (18) the values y and x are taken from the corresponding neutral axes.

Moreover, the cutout stiffeners are acted upon by the tangential loads t (formula (16)), which may be determined by the formulas:

$$\sigma_{a_2} = \pm \frac{ta}{2F_{1ef}} \pm \frac{(\tau - \tau_{cr}) a \delta}{2F_{1ef}} \quad (17b)$$

$$\sigma_{b_2} = \pm \frac{tb}{2F_{2ef}} = \pm \frac{\tau - \tau_{cr}}{2F_{2ef}} b \delta \quad (18b)$$

The distributed load q_r (fig. 5) will produce a tensile stress on the cutout stiffeners parallel to the stringers, the stresses being computed by the formula:

$$\sigma_{l_3} = + \frac{q_r b}{2F_{1ef}} = \frac{\tau - \tau_{cr}}{2F_{1ef}} b \delta \cot \alpha \quad (17c)$$

The tensile stresses in the cutout stiffeners parallel to the ribs are computed by the analogous formula:

$$\sigma_b = \frac{q_{st} a}{2F_{2ef}} = \frac{\tau - \tau_{cr}}{2F_{2ef}} a \delta \tan \alpha \quad (18c)$$

Thus the resultant stresses in the cutout stiffeners parallel to the stringers are determined by the formula:

$$\sigma_a = \frac{\tau - \tau_{cr}}{2} \left[\pm \frac{a^2 y \delta}{12 I_1} \tan \alpha \pm \frac{a \delta}{F_{1ef}} + \frac{b \delta}{F_{1ef}} \cot \alpha \right] \quad (17)$$

and for the stiffeners parallel to the ribs

$$\sigma_b = \frac{\tau - \tau_{cr}}{2} \left[\pm \frac{b^2 x_3}{12 I_2} \cot \alpha \pm \frac{b \delta}{F_{sef}} + \frac{a \delta}{F_{sef}} \tan \alpha \right] \quad (18)$$

In the case where the cutout stiffeners are stringers at the same time, an additional computation must be made for the stresses due to the bending moment.

CONSTRUCTION OF TEST SPECIMENS AND METHOD OF TESTING

With the object of checking the computation formulas by experiment, various specimens were constructed and tested.

A. Construction of Specimens

(a) Thin-walled flat beams tested for bending under a concentrated force.— Beam No. 1 (fig. 7) had no cutouts and consisted of skin, stringers, ribs, and spars. The skin was 1 millimeter thick and the intermediate ribs (fig. 11a) were of duralumin DZ; the stringers were of pressed superduralumin (fig. 11b). The outermost ribs (fig. 11c) and the spars (fig. 11d) were of chromo-molybdenum. The skin was attached to the spars by means of duralumin angles at both sides. The over-all dimensions of the beam were 1340 by 1810 millimeters; the distance between stringers was 150 millimeters and between ribs 540 millimeters.

Beam No. 2 had three window cutouts (fig. 8). The spars, ribs, and stringers were the same as for beam No. 1. The thickness of the skin strip in the region of the cutouts was increased, however, to 1.5 millimeters. One cutout, of rectangular shape, was stiffened by a duralumin frame of U-section (fig. 11e). The oval-shape cutout was stiffened by a frame of the same cross section. The stringers and the ribs served as the frame of the third cutout of rectangular shape.

Beam No. 3 (figs. 9 and 9a) had two window cutouts and differed from beam No. 2 in that the area of the cross section of the frame (fig. 11f) around the oval cutout was increased to double that of the oval frame of beam No. 2. The joints of the curved members of the frame with the straight members were improved. Moreover, the rectangular cutout of the center panel was bordered by stringer sections, that is, the skin was cut out up to the stringers while at the sides the cutout was stiffened by sections of the same type as the stringers.

Beam No. 4 (figs. 10 and 10a) had a door cutout and differed from beam No. 1 in that over the entire center panel

was placed a 3-millimeter skin, to which was riveted a layer of duralumin sheet of 2-millimeter thickness and 915-millimeter height. The contour of the door cutout was stiffened by a frame, the cross section of which is shown in figure 11g.

Beam No. 5 (fig. 10b) likewise had a door cutout and differed from beam No. 4 in that the cross-sectional area of the frame about the cutout (fig. 11h) was doubled. Moreover, the joints between the straight and curved members were strengthened and the butt ends of the stringers were strengthened by means of gussets attached to the intermediate ribs.

(b) Plane panels tested in compression.- Panel No. 1 had no cutouts and consisted of duralumin elements, that is, skin, stringers, and ribs. The over-all dimensions of the panels were the following: length, 620 millimeters and width, 580 millimeters. The distance between the stringers was 140 millimeters, between the ribs 560 millimeters. For the intermediate stringers bulb angle stiffeners, type 24HX-3 (fig. 11b) were used, and for the outermost stringers and ribs type 24HX-5 (fig. 11j) were used. On the side of the smooth skin along the edges of the panel additional shortened stringers of section 24HX-5 were attached in order to provide local stiffening of the parts of the panel weakened most by the cutout while in the case of the panel without cutouts they were attached to give uniformity of construction, thereby enabling a comparison of the test results.

Panel No. 2 (fig. 12) differed from panel No. 1 in that it had a symmetrically placed cutout of 460-millimeter diameter.

Panel No. 3 differed from panel No. 2 in that the contour of the cutout was stiffened by a ring frame of U-section (fig. 11i). The construction of this type of cutout approaches the cutout of the open pilot's cabin.

(c) Plane panels tested in tension.- The center parts of panels Nos. 4 (fig. 14), 5, and 6 (fig. 15) were the same, respectively, as those of panels Nos. 1, 2, and 3. Thus, the panels tested in tension differed from the panels tested in compression only in the lengthened ends for the loading of uniformly distributed forces.

Test Procedure

(a) Each beam was tested under a concentrated load at one end.- Along one side of the specimen, guides were mounted that

permitted it to move only in its plane. At the outermost ribs and spars the tensiometers were mounted in pairs on each side in order to exclude the effect of the bending on the reading of the tensiometers. The deflections of the specimens were measured by instruments placed at intervals of 300 millimeters from each other and connected with the specimen by steel wires (fig. 9a). The first reading was made under a load of 1 ton and the following readings were made for each 800 kilograms. At failure of the beams only the maximum deflections were measured.

(b) Testing of the panels in compression.— The testing of the panels in compression was conducted on Ansler machines of 10 and 100 tons. The ends of the panels were pressed against the planes of the machine. The tensiometers were mounted on the skin, stringers, and stiffener frame along the direction parallel to the stringers. In order to exclude the effect of the bending, during wave formation of the skin, on the readings of the tensiometers the latter were mounted in pairs; that is, on the two sides with a gage length of 10 millimeters. At the outermost stringers and the frame around the cutout the tensiometers were likewise mounted in pairs but with a gage length of 20 millimeters. The readings of the tensiometers were made at 1-ton load intervals.

(c) Testing of the panels in tension.— The specimens were tested in tension by application of a lever system. The tensiometers were mounted in the same manner as for the compression tests but all with a gage length of 20 millimeters. Moreover, additional rows of tensiometers were mounted near the ends.

ANALYSIS OF TEST RESULTS

(a) Results of Bending Tests on the Beams

Table 1 gives the failure loads, the magnitude of the maximum deflections, and the weight characteristics for the beams tested in bending. The stress distribution in the elements of beam No. 1 (without cutouts) is shown on figure 16. These stresses correspond to a load of 5000 kilograms and are given on the figure in kilograms per square centimeter, the circles and lines through them denoting respectively the location and the direction of mounting of the tensiometers.

Figure 17 shows the ratios of the stresses in the elements of beam No. 2 to the stresses in the corresponding elements of beam No. 1. Analogously, on figures 18, 19, and 20 are shown the corresponding ratios of the stresses in the elements of beams Nos. 3, 4, and 5 to the stresses in the corresponding elements of beam No. 1. The minus indicates a change in the sign of the stress.

As may be seen from figure 16, corresponding to beam No. 1, the maximum stresses measured on the waves of the skin were obtained along the diagonal of the beam. This may be explained by the fact that the spars of the beam were not absolutely stiff in bending in the plane of the skin. For completeness of the picture of the nonuniform behavior of the skin in the beam, the test values of the stresses in the skin along the depth of the beam wall (fig. 21a) and along the section perpendicular to the waves (fig. 21b) are given. Figure 21a gives the stresses in the skin of beam No. 1 (fig. 16, section AB) and figure 21b gives the stresses in the skin unstiffened by stringers and cut into strips of 50-millimeter width. (See reference 5.) As may be seen from figures 21a and 21b, the law of distribution of the stresses in the skin both in the case of stiffening by stringers and in the unstiffened skin is the same, that is, the maximum tensile stresses correspond to the center sections of the skin. The stresses decrease toward the stringers.

Remark. For the points where the magnitude of the stresses deviated from the general law of the stress distribution, tensiometers were mounted a second time but the previous results were essentially confirmed. These deviations may be explained by (1) small strains in certain panels of the skin; (2) the waves of the skin encountering the stringers and ribs change their shape and angle of inclination somewhat (fig. 10a).

It is seen on figure 17 that the stresses in the center panel of the skin have as a rule the maximum values. This may be explained by the fact that the stringers acting in compression simultaneously with the skin relieve the skin load to some extent near the stringers.

The stringers, ribs, and lower spar, as may be seen from the signs of the stresses (fig. 16) are under compression; the upper spar and the skin are under tension. The start of equilibrium breakdown of the skin was visually observed at a load of 600 kilograms. The inclination of the waves in the skin to the spars was approximately 38° . The failure of the

specimen occurred under a load of 9600 kilograms as a result of failure of the rivets at the place of attachment of two sheets of the skin under the stringers.

Beam No. 2 (fig. 8) was initially tested only with two cutouts up to a load of 5 tons and then a third cutout was made and the specimen again tested. The results of the later tests are indicated on figure 17 by primes. An increase in the load above 5000 kilograms produced large deformations in the frames around the cutouts. The cutout stiffeners the sections of which are shown in figure 11 buckled out, and at the places where the curved and straight members were joined the rivets were sheared and the beam was ruptured at a load of 5200 kilograms. It should be remarked that the third cutout stiffening, which consisted of stringers and ribs, received a slight deformation at failure of the beam. The effect of the cutouts on the stress distribution may be followed from a comparison of the stress ratios, indicated by primes (section AB, fig. 17), with the values of the stress ratios without primes (of the same section). This comparison shows that the presence of a cutout in the first panel (variant of beam test with three cutouts) gave an increase in the stresses in the center panel, for example, of about three times as compared with case of no cutout in the first panel (variant of beam test with two cutouts). In the second and third panels of the beam, shown on figure 17, the effect of the cutouts was to a large extent eliminated by the use of a stiffening strip of skin and light frames around the cutout.

From the test on beam No. 2 it was found that the light frames placed around the cutout appeared as the weakest parts of the beam. It is therefore necessary to reinforce the cutouts with stronger stiffener sections. The strength of beam No. 2, as may be seen from table 1, was 54.2 percent of that of beam No. 1.

Beam No. 3 had two window cutouts similar to the cutouts of beam No. 2 (figs. 9 and 9a). The strengthening of the cutout stiffeners gave an increase in the failure load up to 800 to 8000 kilograms, which constitutes 83.4 percent of the strength of the beam without cutouts, that is, increased the strength of the beam by 29.2 percent. The beam failed as a result of the large deformations of the skin attached to the stiffener strip, the buckling of the stringer at the boundary between the sheets of skin of different thicknesses and the failure of the rivets. The frame was therefore no longer the weakest part of the beam. Thus an increase in the stiffness of the frame members around the cutout, without

essentially affecting the stress distribution in the skin (figs. 17 and 18), considerably increased the strength of the structure.

Beam No. 4 had a door cutout (figs. 10 and 10a). At a load of 4.5 tons the sections of the frame around the cutout buckled. At a load of 6 tons the thickened skin began to warp. In the panels not having cutouts deep waves were formed (fig. 10a). At a load of 7900 kilograms the frame strip buckled, producing a failure of the rivets which attached it to the ribs. This led to the rupture of the beam. The strength of beam No. 4 was 82.4 percent of that of beam No. 1. In this case, as in the case of beam No. 3, the frame around the cutout was the weakest part of the structure.

In beam No. 5 the contour of the door cutout, similar to the cutout of beam No. 4, was stiffened by a frame the profile cross section of which was doubled, and gussets were mounted to stiffen the joints of the stringers with the ribs. At a load of 8000 kilograms, that is, greater than the rupturing load of beam No. 4, no deformations in the panel with cutout were observed visually. At a load of 8200 kilograms the skin of the first panel near the thickened part (stiffener strip) sharply buckled. A load of 8600 kilograms produced the same deformations as in the skin of the initial panel. At a load of 8800 kilograms the beam failed as a result of the large deformations of the skin joined to its stiffened part and to the failure of the rivets. Thus the substitution of a stiffer frame around the contour of the door cutout raised the overall strength by 10.1 percent, thereby raising the strength to 92.5 percent of that of the beam without cutouts.

The following relation in the behavior of the elements of the beam may be noted here. In the initial skin after loss of equilibrium the depth of the waves increases with increase in the load, and this may lead to one of two ways of beam failure:

1. The frame around the cutout cannot ensure equilibrium of the region with stiffener strip; so the loss of equilibrium of the latter leads to final failure either of the cutout stiffener members or of their joints (case of failure of beam No. 4).

2. The frame assures the stability of the region with stiffener strip. The initial skin having lost its stability and encountering resistance to the spreading of the waves from the initial skin to the stiffener breaks down at the place of a drop in the stiffness (case of failure of beam No.

5). The stresses in the parts of the initial skin attached to the stiffener strip in this case rise, as may be seen from the data on figures 20 and 19. The ratios of the stresses in beam No. 5 to the stresses in beam No. 1 at the place where the initial skin is attached to the stiffener strip are greater (fig. 20) than the corresponding magnitudes in beam No. 4 (fig. 19).

From what has been said above and a consideration of the laws of stress distribution in the regions of the cutouts and the neighboring regions (figs. 19 and 20), the following conclusions may be drawn:

1. When the frame around the cutout is not sufficiently stiff, the stiffener strip of skin buckles in approximately the same manner as the initial skin. Such a frame puts the initial skin at the place of its attachment to the stiffener strip under more favorable conditions but prematurely brings about a failure of the beam as a result of the large deformations of the cutout contour and these deformations bring about the loss of equilibrium of the stiffened region.

2. A sufficiently stiff frame around the cutout prevents the buckling of the stiffener strip but gives rise to a stress concentration in the parts of the nonstiffened skin where it is attached to the stiffener strip, that is, where the stiffness of the skin is different.

With the object of clarifying the effect of the stiffness of the junctions of the outermost ribs with the spars (rigidity of the frame structure), a test was conducted on a frame which was obtained by cutting out all elements adjoining the spars and the outermost ribs. The deflection of the frame was carried to the same value at which the beam without cutouts failed. This deflection was obtained at a load of 400 kilograms. The effect of the frame rigidity of the structure thus constituted about 4 percent.

(b) Results of Test on Panels in Compression

Three panels were tested in compression: one without cutout, a second with an unstiffened cutout (fig. 12), and the third with a cutout stiffened by a ring-shape frame (fig. 13).

In figure 22 the stresses indicated correspond to a load of 5,000 kilograms. In panel No. 1 not having any cutout the

skin lost its equilibrium at a load of 7 tons. The panel failed under a load of 18,900 kilograms as a result of the bending of the stiffeners in two directions. The weakest parts of the specimen were the sections adjoining the butt ends of the shortened stringers which were not stiffened with horizontal stiffeners at the ends. At these places the initial stringers received a fracture. The stresses in the skin, as may be seen from figure 23, were considerably less than in the stringers.

In panel No. 2 the unstiffened contour of the cutout under a load of 3 tons bent along a wavy line. The start of the loss of equilibrium of the skin was observed, however, at a load of 1 ton. With increasing load the depth of the waves of the skin and, in particular, along the contour of the cutout considerably increased. At a load of 9800 kilograms the panel failed. The outermost (initial) stiffeners bent somewhat and at the ends of the shortened stringers received a sharp fracture. The effect of the cutout on the stress distribution in the elements of panel No. 2 is shown in figure 23 by the ratios of the stresses in the elements of panel No. 2 to the stresses in the corresponding elements of panel No. 1.

Panel No. 3, that is, with a cutout stiffened by a ring frame (fig. 13) failed at a load of 10,100 kilograms. The start of the loss of equilibrium in the skin was observed at a load of 2 tons. The weakest region of the panel was the section at which the shortened stringers ended. The stiffener frame of the cutout during failure of the panel showed no deformations observable by the naked eye. On figure 24 are indicated the ratios of the stresses obtained in panel No. 3 to the stresses in panel No. 1. From the data on figures 23 and 24 it is seen that all three middle stringers and the skin between them very weakly assumed the load. The outermost stringers, the adjacent parts of the skin, and the frame of the cutout were strongly overloaded. The local stiffeners in the form of shortened stringers strengthened the minimal section of the panels after which the weakest sections were found to be those to which the shortened stringers did not extend. Owing to the mounting of a frame around the cutout, the part of the skin which was attached to the frame did not lose equilibrium as was the case with the panel with unstiffened cutout.

The breakdown loads of the panels with the unstiffened and stiffened cutouts in percent of load in the panel without cutout were respectively 50.8 and 53.4.

The presence of a frame increased the over-all strength of the panel only by 2.6 percent; while the effect of a cutout in the given case was almost 50 percent. Such a lowering of the strength of a panel with cutouts may be explained chiefly by the insufficient cross-sectional area of the outermost stiffeners. The cross-sectional area of the panel without cutout was

$$F_{tot} = F_{st} + F_{sk} = 5.7 + 5.8 = 11.5 \text{ square centimeters}$$

The cross-sectional areas of the shortened stringers are not taken into account, since they constituted only local stiffeners at the sides of the cutouts. The cross-sectional area of the panel with stiffener cutout was

$$F_{tot} = F_{st} + F_{sk} = 2.4 + 1.2 = 3.6 \text{ square centimeters}$$

that is, constituted 31.6 percent of the cross-sectional area of the panel without cutout.

From what has been said, it follows that the elimination to any considerable extent of the effect of the cutout is possible only by mounting stronger stiffener sections at the sides of the panel. The choice of section should be based on the consideration that the minimum area of the panel cross section should be equal approximately to the cross-sectional area of the panel without cutout.

(c) Results of the Tests on the Panels in Tension

Three panels were tested in tension: panel No. 4 without cutout, No. 5 with an unstiffened cutout, and No. 6 with a stiffened cutout.

At a load of 26 tons on panel No. 4 (fig. 14) several rivets were sheared and the ends of the shortened stringers stood noticeably away from the skin. This may be explained by an eccentricity of the point of load application due to the difference in thickness of the skin and steel plates riveted to the ends of the panel. At a load of 28 tons the panel buckled simultaneously over the entire cross section. The stresses in the elements of panel No. 4 are shown in figure 25.

In panel No. 5 (with unstiffened cutout) the intermediate stringers and the skin between them weakly supported the external load, as may be seen from the ratios of the stresses in the elements of panel No. 5 to the stresses in panel No. 4 (fig. 26). Panel No. 5 failed with buckling of the skin near the unstiffened contour of the cutout at a load of 14.5 tons.

In panel No. 6 the stiffening of the cutout prevented warping of the skin and somewhat increased the supporting capacity of the center part of the panel. The failure of the panel occurred at a load of 16.2 tons. The effect of the stiffened cutout on the redistribution of the stresses is shown in figure 27.

Panels 5 and 6 had 51.7 and 54.3 percent, respectively, of the strength of panel No. 4. As in the case of the compression tests the deciding factor was not the local stiffening in the form of shortened stringers or frames around the cutouts but the increase in the cross-sectional area of the outermost stiffeners since these must in the end take up the external load.

CONCLUSIONS

(a) Cutout at the Sides of a Stringer Monocoque Fuselage

On the basis of the preceding computations and test results, it may be remarked that the weakening effect of cutouts may to a large extent be eliminated by placing around the cutout a skin strip (fig. 6) the thickness and width of which are chosen by formula (13). Moreover, it is necessary to put around the cutout a frame having members possessing sufficient stiffness to bending in the plane of the skin and normal to it. The loads associated with the frame are determined by formulas (17) and (18). The joints of the frame members also should be of sufficient strength.

The most choice of the stiffener elements of the cutout may be considered that for which the cutout region is no longer the weakest part of the side of the fuselage and the local stress concentration in the skin near the stiffener strip is not large. This condition may be attained by mounting a stiff frame capable of preventing loss of equilibrium of the stiffened region of the skin. Moreover, the thickness of the stiffener strip should be equal to or somewhat greater than the thickness of the initial skin. Mounting

a strip the thickness of which considerably exceeds the thickness of the initial skin is not recommended, because of the sharp drop in the stiffness of the beam that may lower its strength.

If the fuselage has longerons extending to the cutouts, then in computing the longerons account should be taken of the loads computed by formulas (7) and (8).

(b) Cutouts in the Sides of

a Monocoque Fuselage without Stringers

The cutouts in the sides of a fuselage not having longitudinal stiffeners must be stiffened by attaching around the cutout a skin strip having thickness and width chosen by formula (13) and placing strong stiffeners around the cutout. The horizontal members should extend to the second ribs.

NUMERICAL EXAMPLE OF A BEAM COMPUTATION

(a) Computation of a Beam without Cutouts

A numerical example of the computation applicable to tested beam No. 1 of a multipaneled beam constructed of various materials is given below.

Computation Data

External force	$P = 5000 \text{ kg}$
Height of beam	$H = 1270 \text{ mm}$
Distance between stringers	$h = 150 \text{ mm}$
Length of beam	$L = 1730 \text{ mm}$
Distance between ribs	$l = 570 \text{ mm}$
Cross-sectional area of spar	$F_{sp} = 10.2 \text{ cm}^2$
Cross-sectional area of outermost ribs	$F_I = 7.8 \text{ cm}^2$

Cross-sectional area of
intermediate ribs $F_{II} = 1.23 \text{ cm}^2$

Cross-sectional area of
stringer $F_{st} = 1.1 \text{ cm}^2$

Thickness of skin $\delta = 1 \text{ mm}$

Elasticity modulus of spars
and end ribs $E_{st} = 2.1 \times 10^6 \text{ kg/cm}^2$

Elasticity modulus of walls,
intermediate ribs and stringers $E_{dur} = 7.2 \times 10^5$

Compute the ordinate of the neutral axis of the effective section of the beam (fig. 28). In the region of the beam under tension it will be assumed that 85 percent of the skin takes part and in the region under compression strips having a width 30 times the thickness adjacent to the stiffeners (reference 6).

In order that it may be possible to assume in computing the cross-sectional areas of the beam that all its elements consist of the same material - for example, of duralumin - multiply the cross-sectional areas of the steel elements by the ratio of moduli:

$$\frac{E_{st}}{E_{dur}} = \frac{2.1 \times 10^6}{7.2 \times 10^5}$$

In this case the ordinate of the center of gravity according to the scheme of the beam (fig. 28) will be:

$$y_{cg} = \frac{\left(0,425 h \delta + F_{sp} \frac{E_{st}}{E_{dur}}\right) \bar{y}_1 + (F_{str} + 0,85 h \delta) (\bar{y}_2 + \bar{y}_3 + \bar{y}_4 + 0,5 \bar{y}_5) +}{2 F_{sp} \frac{E_{st}}{E_{dur}} + 7 F_{str} + 4 \delta (0,85 h + 30 \delta)} + \frac{(F_{str} + 30 \delta^2) (0,5 \bar{y}_5 + \bar{y}_6 + \bar{y}_7 + \bar{y}_8)}{2 F_{sp} \frac{E_{st}}{E_{dur}} + 7 F_{str} + 4 \delta (0,85 h + 30 \delta)} =$$

$$= \frac{\left(0,425 \cdot 15 \cdot 0,1 + 10,2 \frac{2,1 \cdot 10^6}{7,2 \cdot 10^5}\right) 127 + (1,1 + 0,85 \cdot 15 \cdot 0,1) (108,5 +}{2 \cdot 10,2 \frac{2,1 \cdot 10^6}{7,2 \cdot 10^5} + 7 \cdot 1,1 + 4 \cdot 0,1 (0,85 \cdot 15 + 30 \cdot 0,1)} + \frac{93,5 + 78,5 + 31,75) + (1,1 + 30 \cdot 0,01) (31,75 + 48,5 + 33,5 + 18,5)}{2 \cdot 10,2 \frac{2,1 \cdot 10^6}{7,2 \cdot 10^5} + 7 \cdot 1,1 + 4 \cdot 0,1 (0,85 \cdot 15 + 30 \cdot 0,1)} = 65 \text{ cm.}$$

Make use of the computed value y_{cg} and the notation of figure 28 to compute the value of the moment of inertia of the effective beam section:

$$I_{ef} = \left(F_{sp} \frac{E_{st}}{E_{dur}} + 0,425 h \delta\right) y_1^2 + (F_{str} + 0,85 h \delta) \times$$

$$\times (y_2^2 + y_3^2 + y_4^2 + 0,5 y_5^2) + (F_{str} + 30 \delta^2) (0,5 y_5^2 +$$

$$+ y_6^2 + y_7^2 + y_8^2) + \left(F_{sp} \frac{E_{st}}{E_{dur}} + 15 \delta^2\right) y_9^2 =$$

$$= \left(10,2 \frac{2,1 \cdot 10^6}{7,2 \cdot 10^5} + 0,425 \cdot 15 \cdot 0,1\right) 62^2 +$$

$$+ (1,1 + 0,85 \cdot 15 \cdot 0,1) (43,5^2 + 28,5^2 +$$

$$+ 13,5^2 + 0,5 \cdot 1,5^2) + (1,1 + 30 \cdot 0,01) (0,5 \cdot 15^2 + 16,5^2 +$$

$$+ 31,5^2 + 46,5^2) + \left(10,2 \frac{2,1 \cdot 10^6}{7,2 \cdot 10^5} + 15 \cdot 0,01\right) 65^2 \cong$$

$$\cong 255\,000 \text{ cm}^4 = I_{dur}$$

If all elements of the beam are reduced to steel

$$I_{st} = I_{dur} \frac{E_{dur}}{E_{st}} = 87\,500 \text{ cm}^4.$$

The static moment is obtained as:

$$S_{red} = \left(F_{sp} \frac{E_{st}}{E_{dur}} + 0,425 h \delta\right) y_1 + (F_{str} + 0,85 h \delta) (y_2 +$$

$$+ y_3 + y_4) \cong 2\,090 \text{ cm}^3.$$

Compute the maximum tangential stress by formula (4):

$$\tau = \frac{QS}{I_s} = \frac{5000 \cdot 2090}{255000 \cdot 0,1} = 410 \text{ kg/cm}^2$$

By formula (5) compute the critical tangential stress in the skin of one panel:

$$\tau_{cr} = 34300 \left(110 + \frac{75}{\beta^2} \right) \left(\frac{\delta}{h} \right)^2 = 34300 \left(110 + \frac{75}{5,72} 15^2 \right) \left(\frac{0,1}{15} \right)^2 = 176 \text{ kg/cm}^2$$

The value of k is determined by formula (3):

$$k = \frac{1}{\frac{2\tau}{\tau_{cr}} - 1} = \frac{1}{\frac{2 \cdot 410}{176} - 1} = 0,273$$

The angle of inclination of the waves in the skin to the spars is determined by the formula (reference 5):

$$\begin{aligned} \operatorname{tg} \alpha &= \sqrt[4]{\frac{1 + \frac{h^2}{2F_{st}} \frac{1-k}{1+\mu k}}{1 + \frac{b^2}{F_{st}} \frac{1-k}{1+\mu k}}} \\ &= \sqrt[4]{\frac{1 + \frac{15 \cdot 0,1}{2 \cdot 1,4} \frac{1-0,273}{1+0,3 \cdot 0,273}}{1 + \frac{57 \cdot 0,1}{1,53} \frac{1-0,273}{1+0,3 \cdot 0,273}}} = 0,787; \alpha = 38^\circ. \end{aligned}$$

The tensile stress is computed by formula (1):

$$\sigma_1 = \frac{2\tau - \tau_{cr}}{\sin 2\alpha} = \frac{2 \cdot 410 - 176}{0,97} = 663 \text{ kg/cm}^2$$

The stresses in the spars, stringers and ribs are computed respectively by formulas (7), (8), (9), (10a), and (10) taking account of the effect of the moduli of the different materials of the various parts of the beam.

The tensile stress in the top spar is

$$\begin{aligned} \sigma_{spt} &= + \frac{M}{I_{ef}} y_s - (\tau - \tau_{cr}) \frac{\delta}{F_{sp}} \frac{H - (H - k_1) \frac{E_{dar}}{E_{st}}}{2} \operatorname{ctg} \alpha = \\ &= \frac{5000 \cdot 142}{87500} 62 - (410 - 176) \frac{0,1}{10,32} \times \\ &\times \frac{127 - (127 - 22) \frac{7,2 \cdot 10^4}{2,1 \cdot 10^4}}{2} \cdot 1,28 = 504 - 132 = 372 \text{ kg/cm}^2 \end{aligned}$$

The compressive stress in the bottom spar is

$$\begin{aligned} \sigma_{sp} &= -\frac{M}{I_{ef}} y_n - (\tau - \tau_{cr}) \frac{\delta}{F_{sp}} \frac{H - (H - h) \frac{E_{dur}}{E_{st}}}{2} \operatorname{ctg} \alpha = \\ &= -\frac{5000 \cdot 142}{87500} 65 - (410 - 176) \frac{0,1}{10,32} \times \\ &\times \frac{127 - (127 - 22) \frac{7,2 \cdot 10^3}{2,1 \cdot 10^3}}{2} \cdot 1,28 = -526 - 132 = -658 \text{ kg/cm}^2 \end{aligned}$$

The stress in the stringers:

$$\begin{aligned} \sigma_{1str} &= \pm \frac{M}{I_{dur}} y - (\tau - \tau_{cr}) \frac{h E_{dur}}{F_{str} E_{st}} \operatorname{ctg} \alpha = \\ &= \frac{5000 \cdot 142}{255000} 13,5 - (410 - 176) \frac{15 \cdot 0,1 \cdot 7,2 \cdot 10^3}{1,4 \cdot 2,1 \cdot 10^3} 1,28 = \\ &= 38 - 110 = -72 \text{ kg/cm}^2 \end{aligned}$$

$$\begin{aligned} \sigma_{2str} &= \pm \frac{M}{I_{dur}} y - (\tau - \tau_{cr}) \frac{h E_{dur}}{F_{str} E_{st}} = \\ &= \frac{5000 \cdot 31}{255000} 13,5 - (410 - 176) \frac{15 \cdot 0,1 \cdot 7,2 \cdot 10^3}{1,4 \cdot 2,1 \cdot 10^3} 1,28 = \\ &= 8,2 - 110 = -102 \text{ kg/cm}^2. \end{aligned}$$

The stress in an intermediate rib:

$$\begin{aligned} \sigma_{ri} &= -(\tau - \tau_{cr}) \frac{B E_{dur}}{F_i E_{st}} \operatorname{tg} \alpha = -(410 - 176) \times \\ &\times \frac{57 \cdot 0,1 \cdot 7,2 \cdot 10^3}{1,53 \cdot 2,1 \cdot 10^3} 0,78 = -234 \end{aligned}$$

The stress in an outermost rib:

$$\begin{aligned} \sigma_{ro} &= -(\tau - \tau_{cr}) \left(\frac{L - (L - l) \frac{E_{dur}}{E_{st}}}{2 F_{II}} \delta \operatorname{tg} \alpha + \frac{y^2}{F_{II}} \right) = \\ &= (410 - 176) \left(\frac{173 - (173 - 57) \frac{7,2 \cdot 10^3}{2,1 \cdot 10^3}}{2 \cdot 7,95} \cdot 0,1 \cdot 0,78 + \frac{101 \cdot 0,1}{7,95} \right) = \\ &= -450 \text{ kg/cm}^2 \end{aligned}$$

A comparison of the magnitude of the stresses obtained by computation and by experiment is given in table 2.

TABLE 2

Number	Place of Stress	Computed stress (kg/cm ²)	Experimental stress (kg/cm ²)	Remarks
1	Skin, σ_1	663	637	Experimental mean stress
2	Upper spar, $\sigma_{u\ sp}$	372	373	
3	Lower spar, $\sigma_{l\ sp}$	-658	-471	
4	Stringer, σ_{st}	-72 -102	-60.4 -106	Stresses in stringer of various panels
5	Intermediate rib, σ_{ri}	-234	-286	Experimental mean stress
6	End rib, σ_{re}	-450	-517	

(b) Computation of Stiffening of a Cutout

The stiffening of one cutout in the second panel of beam No. 3 shown in figure 9 is computed below.

The increase in the thickness of the skin is computed by formula (13):

$$\delta' = \frac{\sigma_1 b \delta}{\sigma_1' b'} = \frac{663 \cdot 280 \cdot 1}{663 \cdot 340} \approx 0,8.$$

The contour of the window cutout was stiffened by the angle profiles type 24HX-3 (fig. 11b). The stress in the members parallel to the stringers is determined by formula (17):

$$\begin{aligned} \sigma_a &= \frac{\tau - \tau_{cr}}{2} - \left[\pm \frac{a_2 y \delta}{12 I_1} \operatorname{tg} \alpha \pm \frac{a \delta}{F_{ef}} + \frac{b \delta}{F_{ef}} \operatorname{ctg} \alpha \right] = \\ &= \frac{410 - 176}{2} \left(\pm \frac{40^2 \cdot 8,5 \cdot 0,1}{12 \cdot 184,7} 0,78 \pm \frac{40 \cdot 0,1}{3,74} + \right. \\ &\quad \left. + \frac{28 \cdot 0,1}{3,74} 1,28 \right) = +294 \text{ or } -69,2 \text{ kg/cm}^2 \end{aligned}$$

The moment of inertia I_1 is composed of those for the skin strip section of thickness $\delta + \delta'$ and the attached stiffener members around the cutout and nearest to it, so that I_1 is computed for an I-shape section:

$$I_1 = \frac{\delta b^3}{12} + \frac{F_{ef} (b-2)^2}{2} =$$

$$= \frac{0,15 \cdot 17^3}{12} + \frac{1,1 \cdot 225}{2} = 184 \text{ cm}^4.$$

The stresses in the stiffener frame members parallel to the ribs are determined by formula (18):

$$\sigma_b = \frac{\tau - \tau_{er}}{2} \left(\pm \frac{b^2 x \delta}{12 I_2} \operatorname{ctg} \alpha \pm \frac{b \delta}{F_{2ef}} + \frac{a \delta}{F_{2ef}} \operatorname{tg} \alpha \right) =$$

$$= \frac{410 - 176}{2} \left(\pm \frac{28^2 \cdot 4,3 \cdot 0,1}{12 \cdot 33,4} 1,28 \pm \frac{28 \cdot 0,1}{3,08} + \frac{40 \cdot 0,1}{3,08} 0,78 \right) =$$

$$= +254 \text{ kg/cm}^2 \text{ or } -17,5 \text{ kg/cm}^2$$

I_2 is given by

$$I_2 = \frac{\delta a^3}{12} + \frac{F_{ef} (a-2)^2}{2} = \frac{0,15 \cdot 640}{12} + \frac{1,1 \cdot 6,8^2}{2} = 33,4 \text{ cm}^4.$$

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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3. Timoshenko, S., and Lessells, J. M.: Applied Elasticity Theory.
4. Naiman, M. I.: Stress in Beam with Rounded Opening. CAHI Rep. No. 313, 1937.
5. Strigunov, V. M.: Theoretical and Experimental Investigation of Thin-Walled Beams. CAHI Rep. No. 349, 1938.
6. Strigunov, V. M.: Stress Analysis of Metal Fuselages. CAHI Rep. No. 435, 1939.

TABLE 1

Beam number	Type of beam	Failure load (kg)	Percent of weakening by cutout (reference to P = 9600 kg)	Weight of beam (kg)	Weight of duralumin elements of beam (kg)	Maximum deflections for P = 5000 kg (mm)
1	Without cutouts	9600	--	45.3	10.8	6.11
2	Three window cutouts	5200	45.8	44.9	10.4	8.72
3	Two window cutouts	8000	16.6	45.3	10.8	7.78
4	Door cutout stiffened by a light frame	7900	17.6	46.3	11.8	8.12
5	Door cutout stiffened by a strong frame	8800	8.5	46.6	12.1	7.18

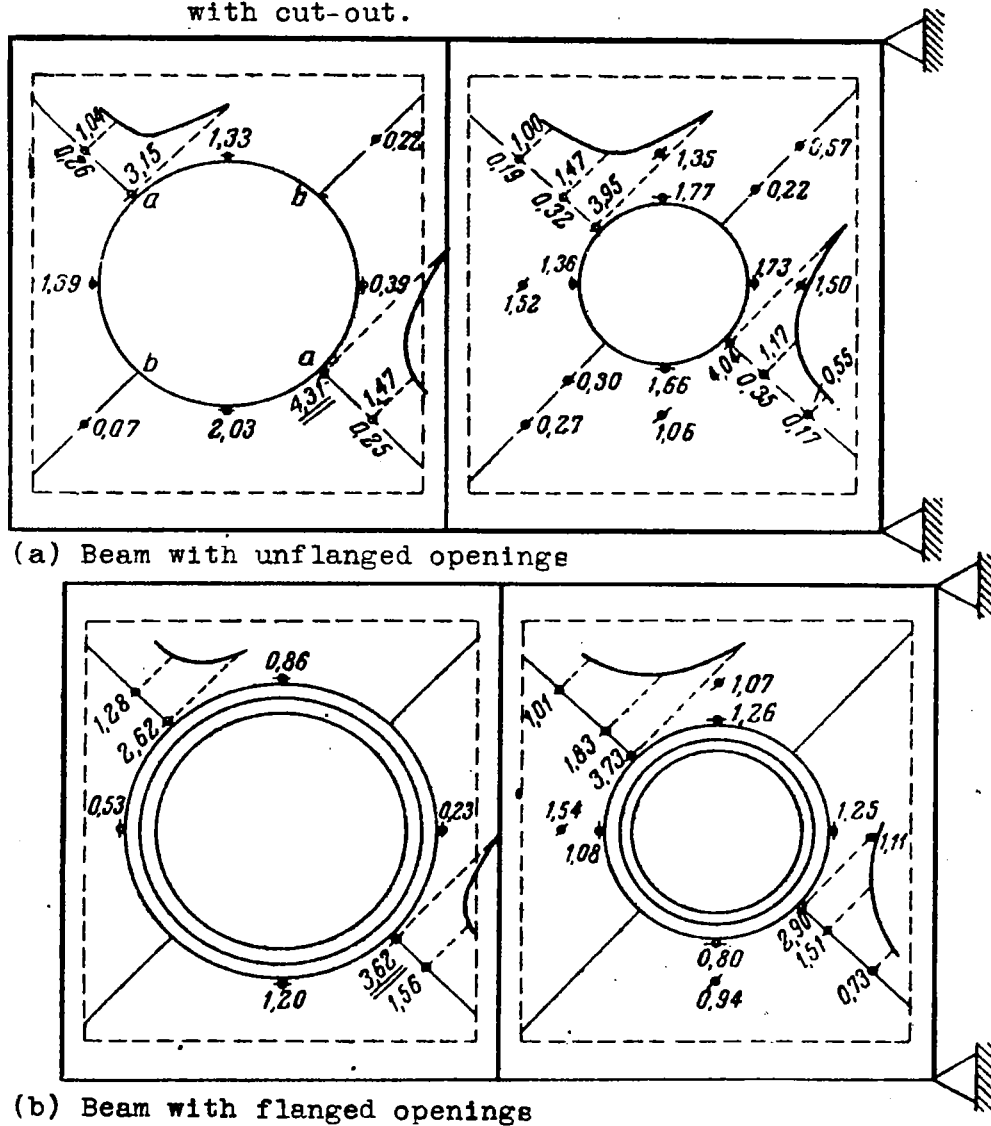
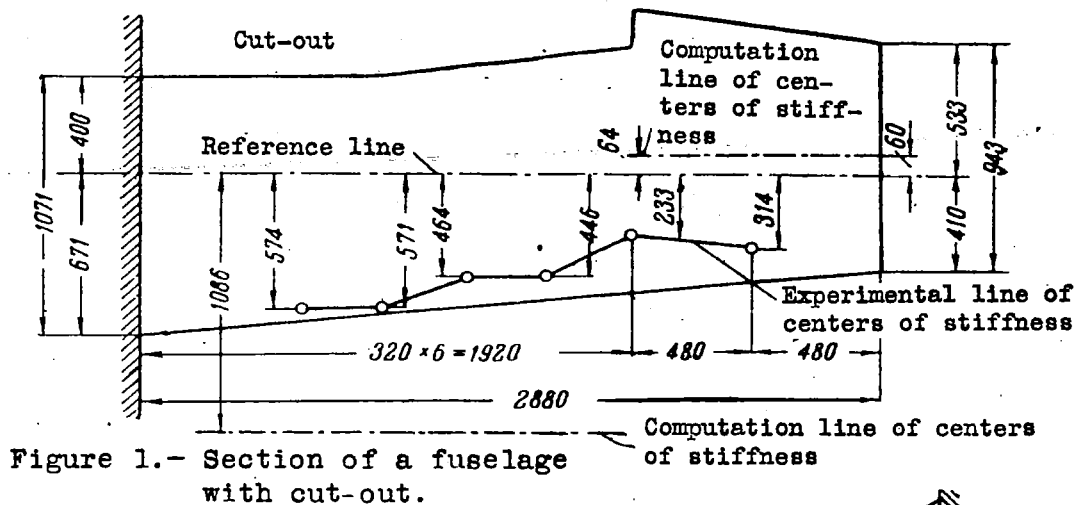


Figure 2.- Ratio of stresses obtained in a beam with cut-outs to the stresses in a beam without cut-outs.

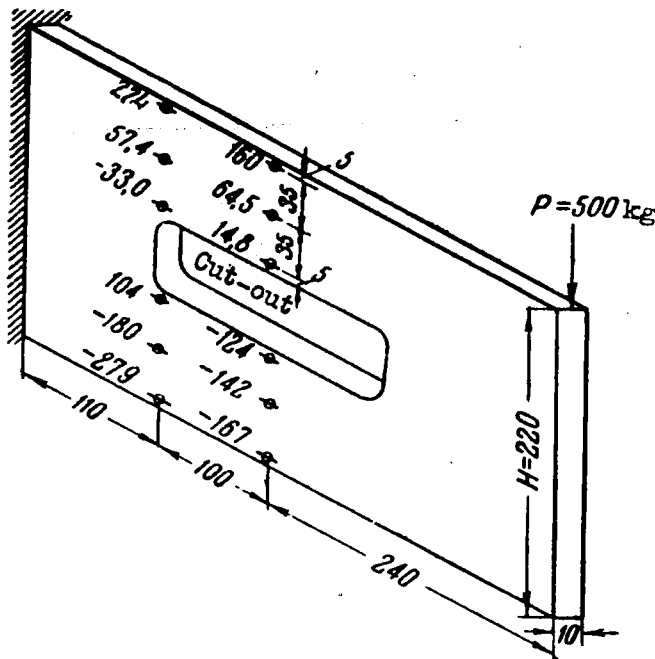


Figure 3.- Sketch of test specimen and value of experimental normal stresses in kg/cm^2 obtained for the specimen with cut-out at $0.264 H$.

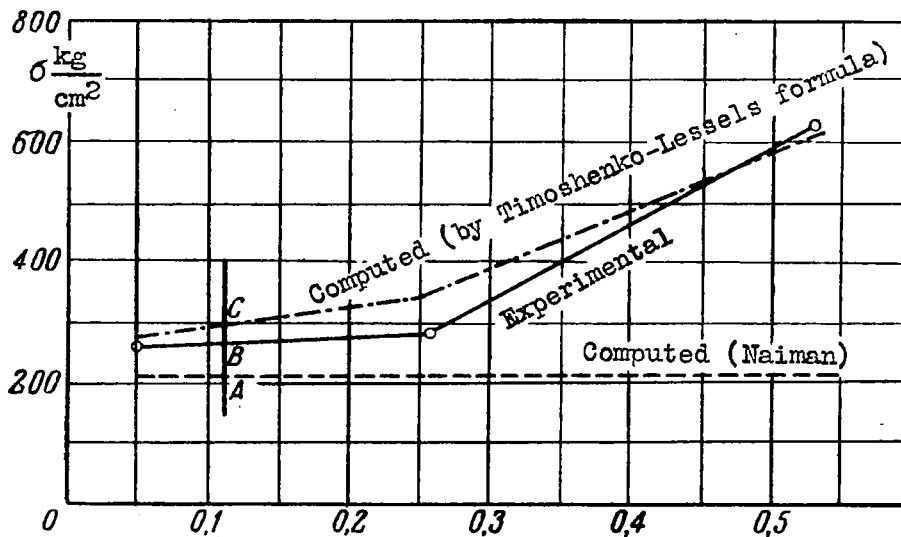


Figure 4.- Dependence of the maximum normal stresses on the depth of the cut-out, expressed as a fraction of the total depth H of the beam shown in figure 3.

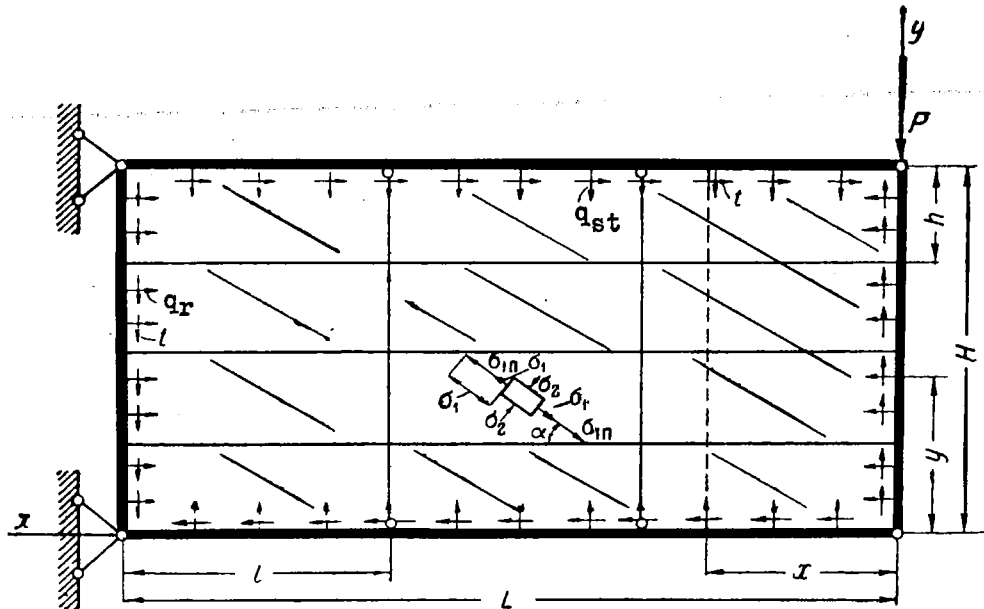


Figure 5.- Stress distributions in the panels of a thin-walled beam at loss of equilibrium.

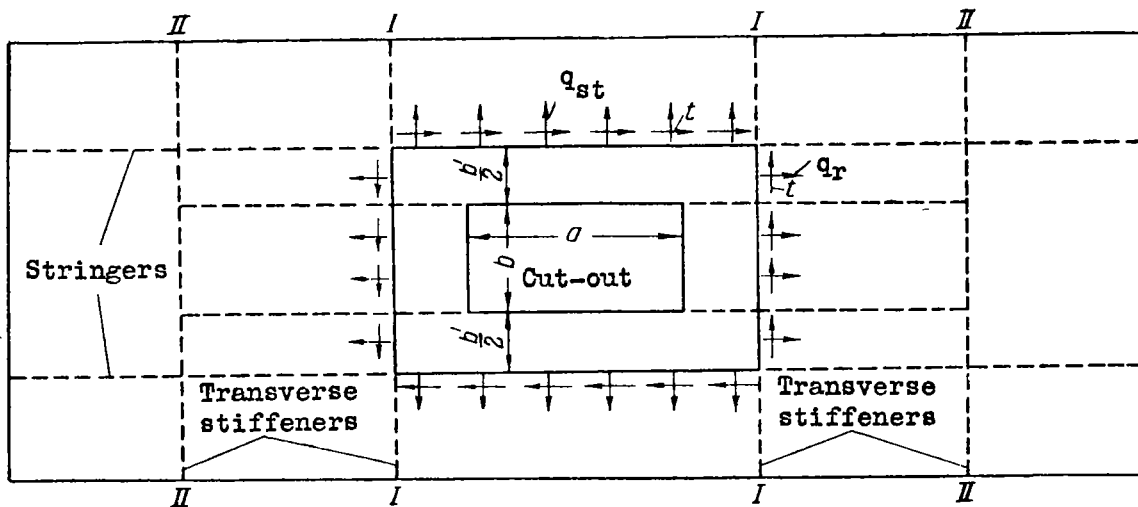


Figure 6.- Stiffener strip around cut-out.

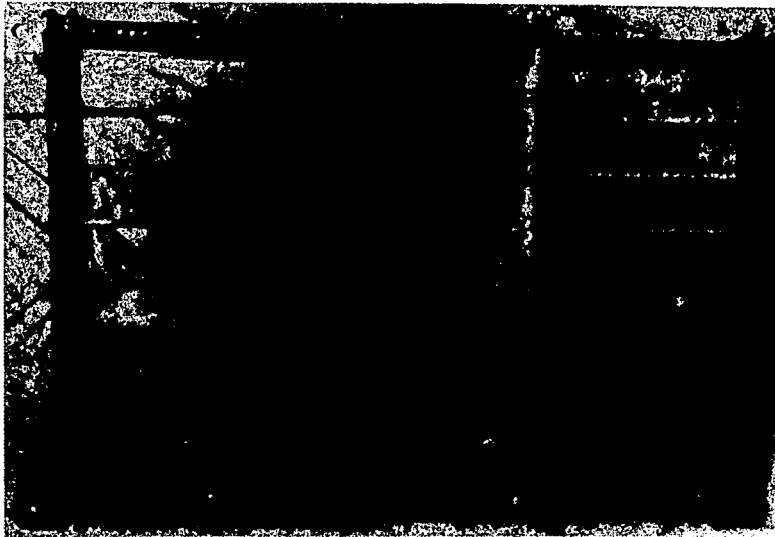


Figure 7.- View of beam no. 1 after failure,
 $P_{fail} = 9600$ kg.



Figure 8.- View of beam no. 2, $P_{fail} = 5200$ kg.

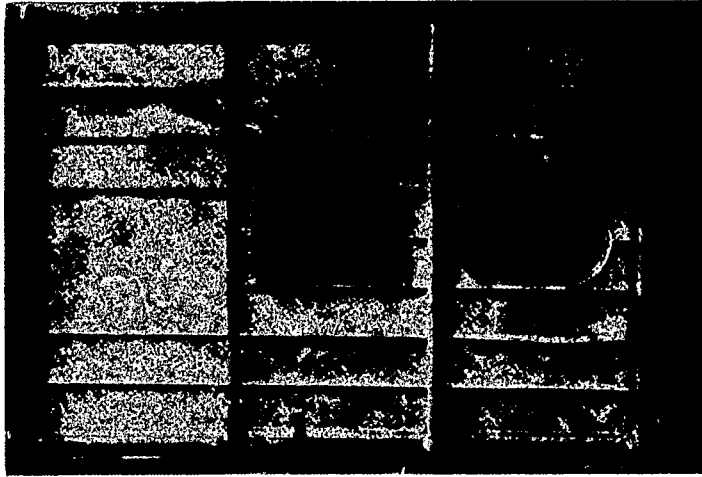


Figure 9.- View of beam no. 3, $P_{fail} = 8000$ kg.



Figure 9a.- View of beam no. 3 under load, with tensiometers mounted.



Figure 10.- View of beam no. 4
after failure and
guide beams, $P_{fail} = 7900$ kg.

Figure 10a.- View of
beam no. 4
under load

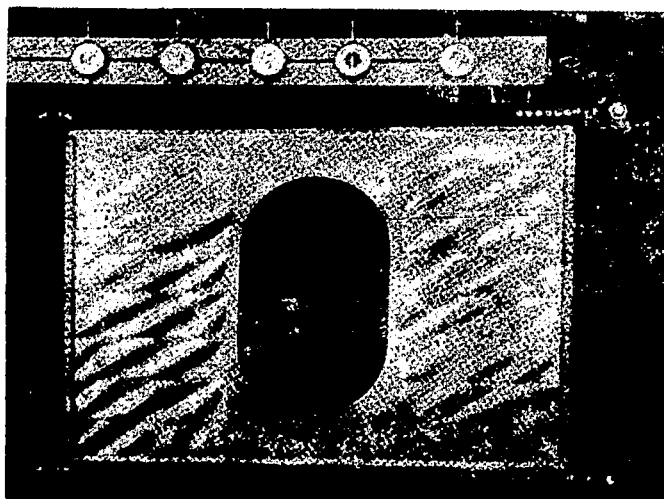
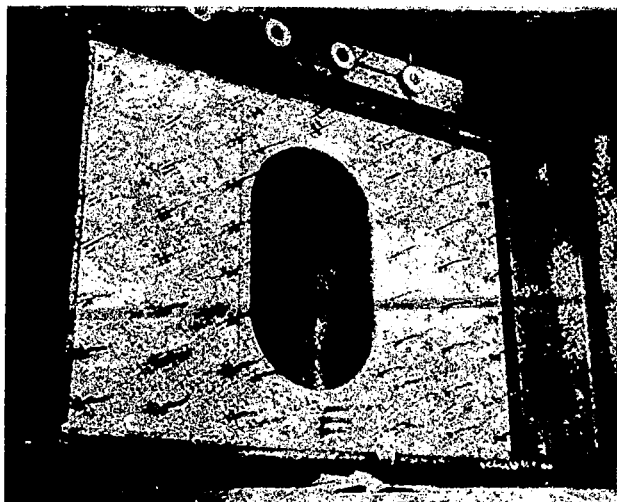


Figure 10b.- View of
beam no.
5 under load, with
tensiometers mounted,
 $P_{fail} = 8800$ kg.



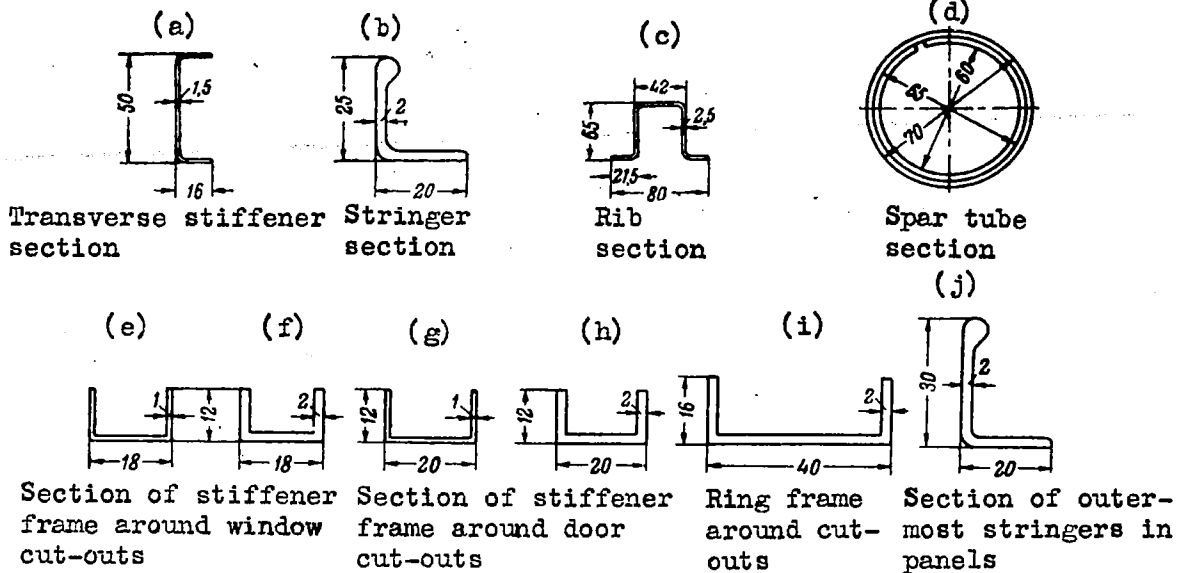
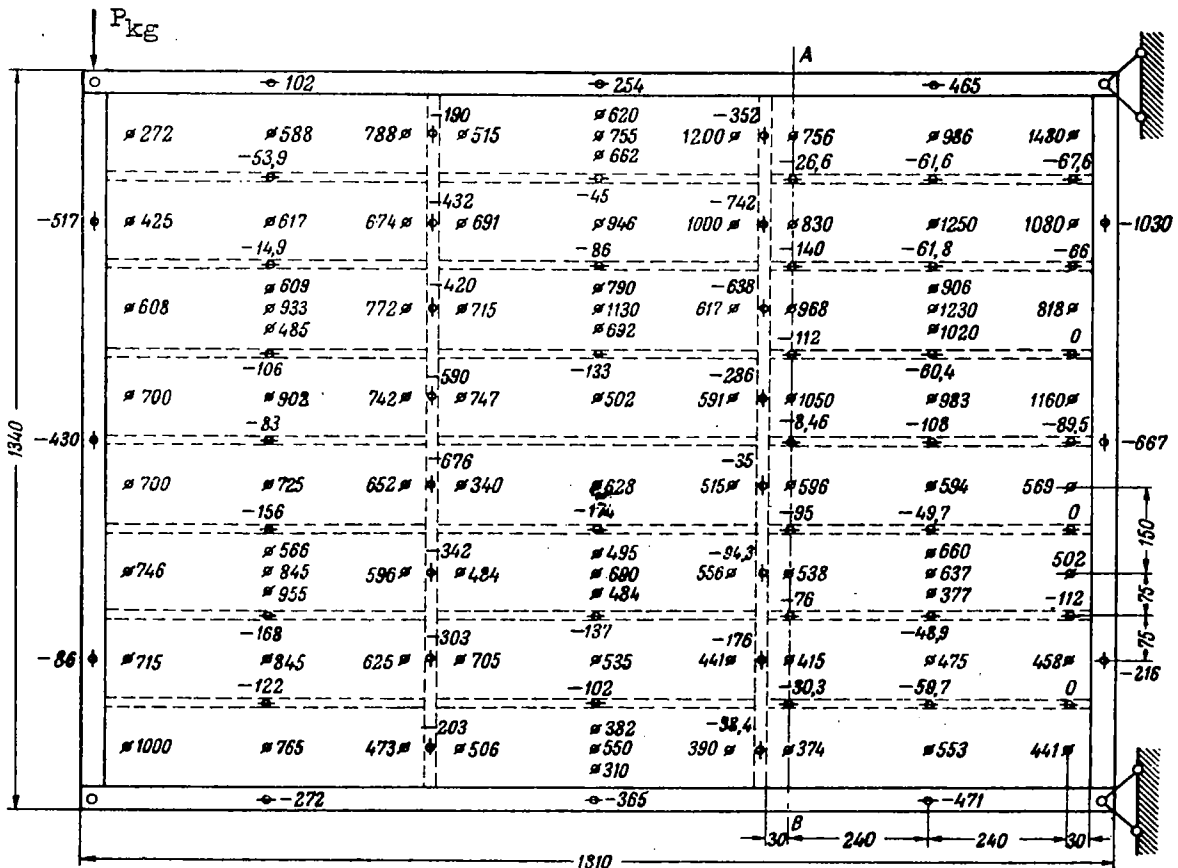


Figure 11.- Cross sections of stiffeners in tested beams and panels.



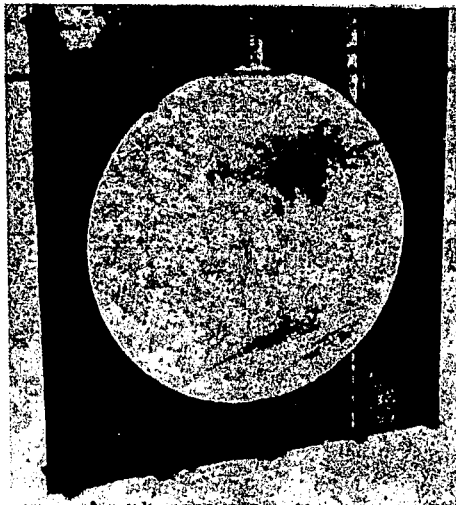


Figure 12.- View of panel no. 2 after failure, $P_{fail} = 9800$ kg.

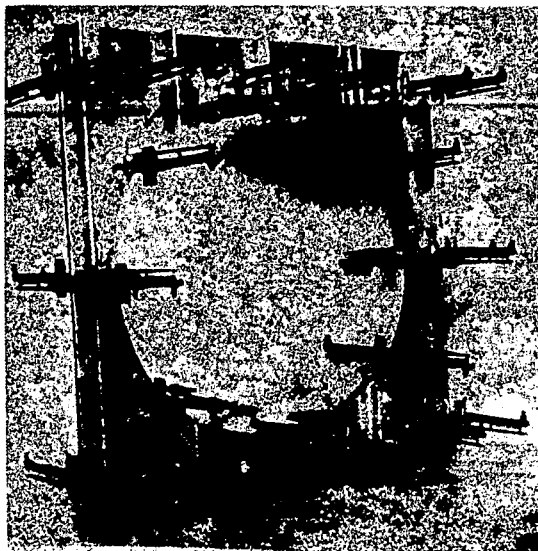


Figure 13.- View of panel no. 3 after failure, $P_{fail} = 10100$ kg.

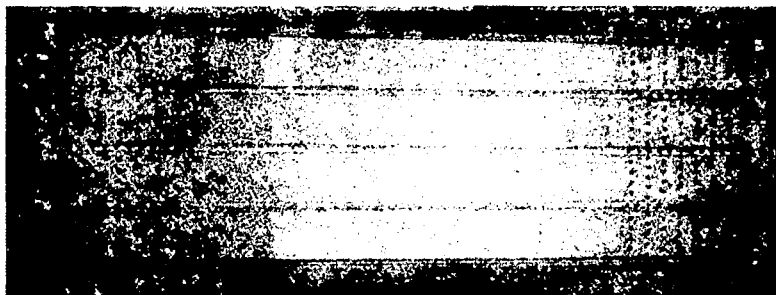
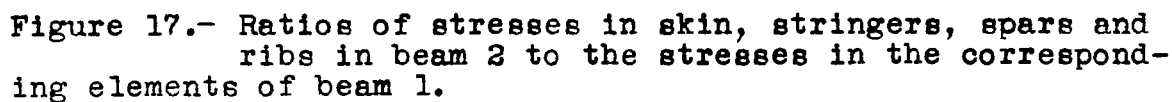


Figure 14.- View of panel no. 4 before failure, $P_{fail} = 28000$ kg.

Figure 15.- View of panel no. 6 before failure with tensiometers mounted, $P_{fail} = 16200$ kg.





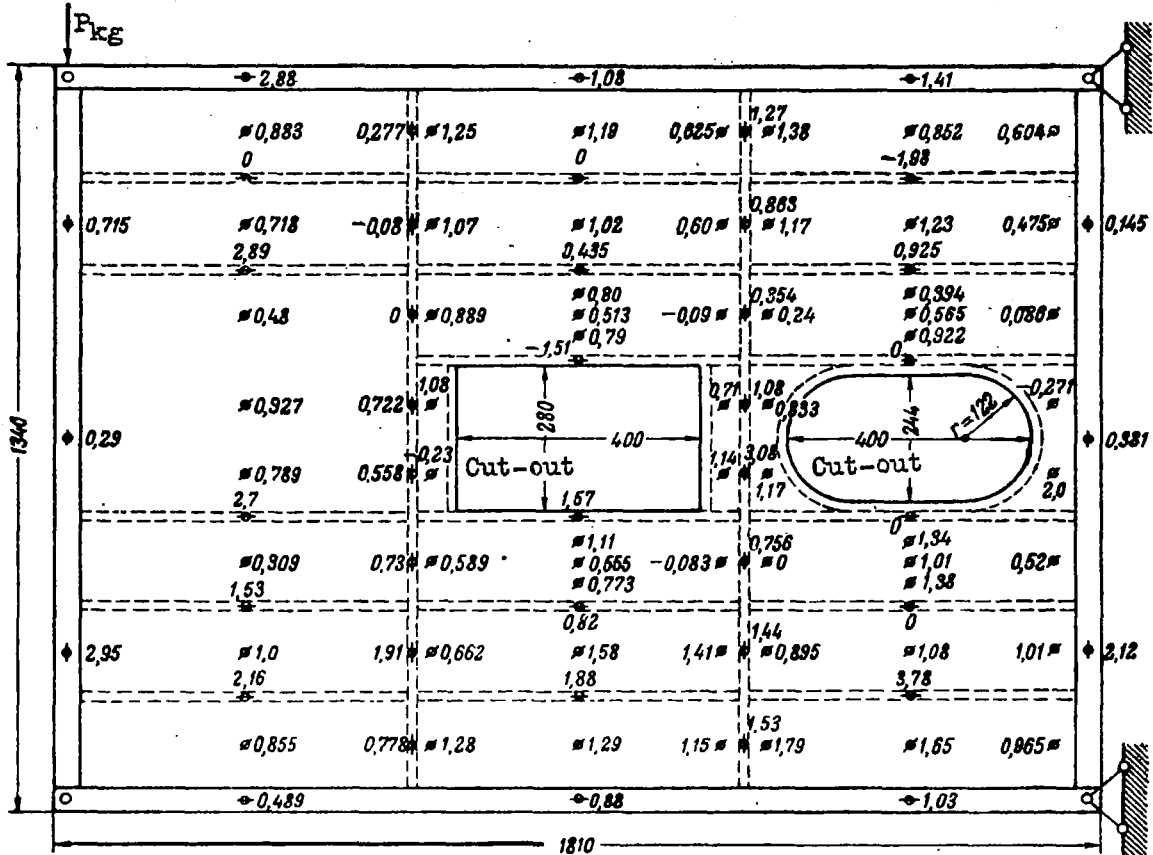


Figure 18.- Ratios of stresses in skin, stringers, spars and ribs of beam 3 to the stresses in the corresponding elements of beam 1.

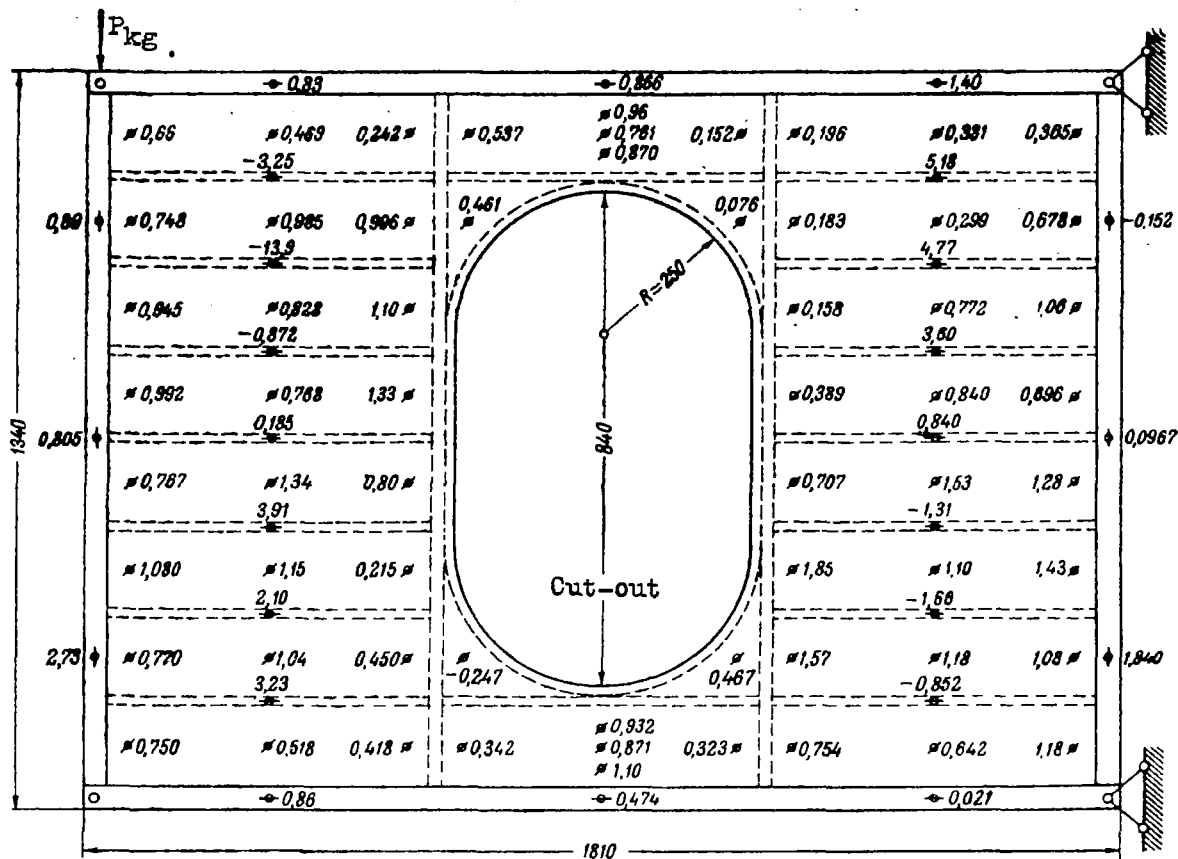


Figure 19.— Ratios of stresses in skin, stringers, spars and ribs of beam 4 to the stresses in the corresponding elements of beam 1.

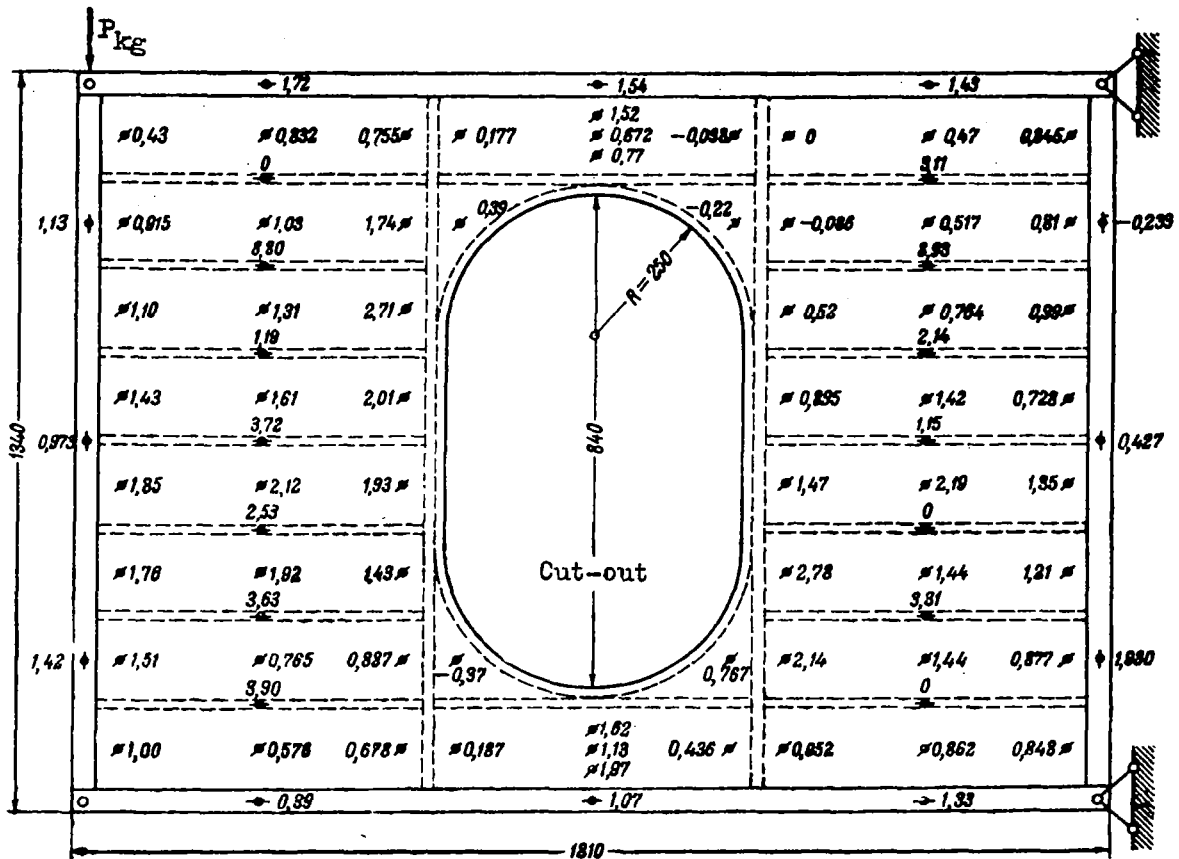


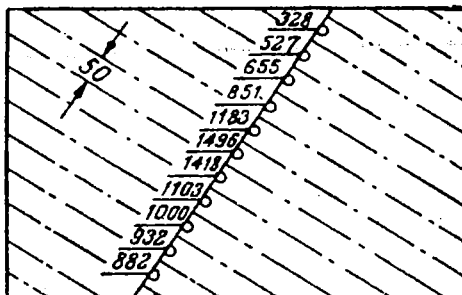
Figure 20.- Ratios of stresses in skin, stringers, spars and ribs of beam 5 to the stresses in the corresponding elements of beam 1.

(a)

	756	
	830	
	968	
	1050	
	596	
	538	
	415	
	374	

Stresses in skin stiffened
by stringers

(b)



Stresses in smooth skin
cut into strips

Figure 21.- Stress distribution (kg/cm^2) in the skin during loss of equilibrium.

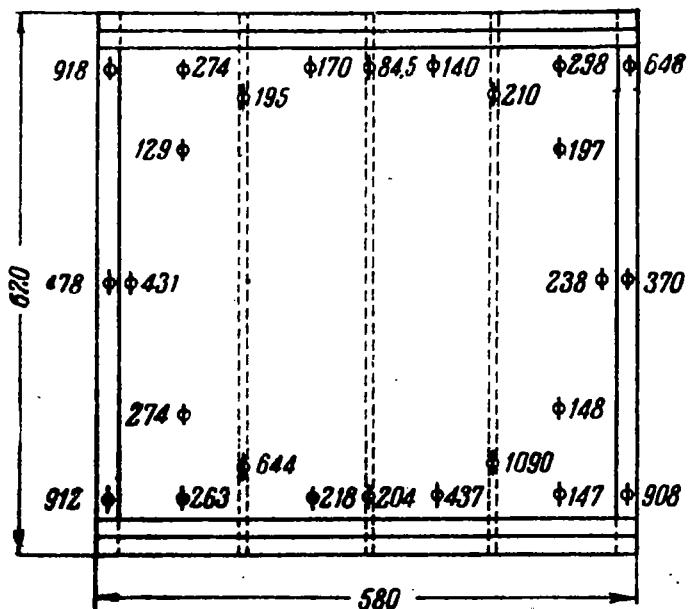


Figure 22.- Stresses (kg/cm^2) in skin and stringers of panel 1.

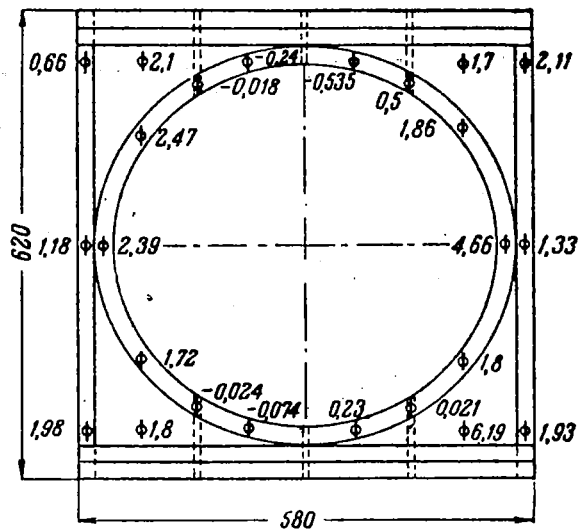


Figure 24.- Ratios of stresses in skin and stringers of panel 3 to the stresses in the corresponding elements of panel 1.

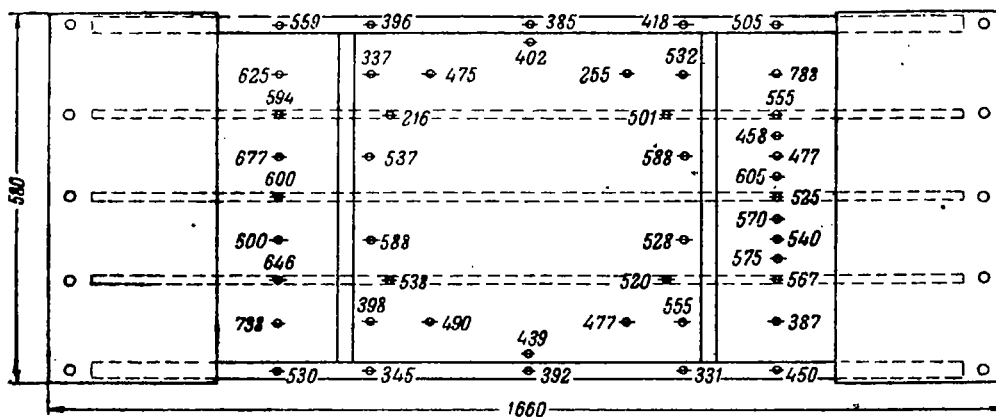
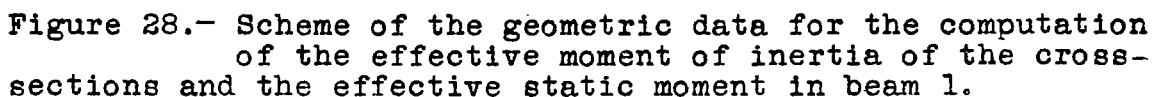
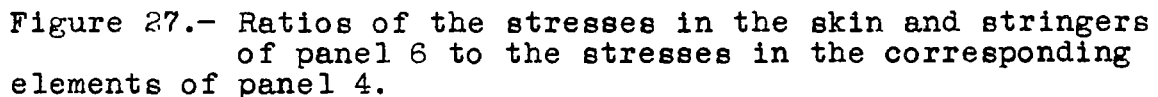
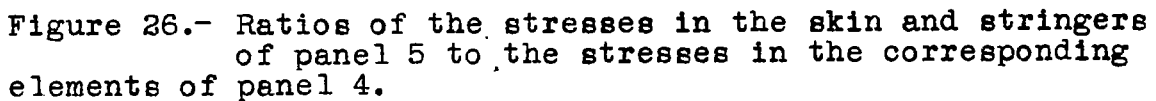


Figure 25.- Stresses (kg/cm²) in the skin and stringers of panel 4.





3 1176 01440 7838

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~~Camber~~

Stressed skin stiffener combinations - Strong
Compression

Fuselages, Cut out

Beams - Bending

Beams - Stresses
Effect of cut-outs

Loads - Beams

Fuselages, Monocoque - Cut out